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ENVIRONMENTAL BENEFITS OF CHEMICAL PROPULSION

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The benefits of chemical propulsion are tightly linked to the measurement and understanding of global climate change and Earth Observation. Anthropogenic and natural influences affecting the Earth system are recognized internationally as having potentially adverse, global consequences over the long term, threatening the current standards for quality of life. Measurement of fossil fuel resources, fish, wildlife, metals and minerals, once performed with dousing rods and exploration parties may now be accomplished via satellite on a global scale. Thus, the availability of chemical propulsion allows a measured, sustainable utilization of Earth's renewable resources, and an informed utilization of the non-renewable ones. The state-of-the-art technology available, enables a quality of life to exist that has never before been possible. The consequent human impacts to the environment are also at previously unseen levels. It is only through effective stewardship of the global resources, which mandates comprehensive measurement capabilities, that we can understand and guide makind's occupation of the Earth.

It is important to comprehend, in context, the issues associated with our current understanding of global change phenomenon. While the implications of any shift in climate are far reaching and without regard for international boundaries, myopic decisions, based on incomplete knowledge of our Earth system, can ultimately do more harm than good to our environment and economy. Given the current economic realities, significant climate shifts, if they do occur, will have global consequences and not be limited to the specific, climate affected regions. In response to these identified global change issues, a number of research and coordinating bodies for Earth science disciplines have emerged throughout the world.[1,2,3,4] The nature of these issues is quite complex, as are the scopes of the international efforts. Figure 1 represents, in summary form, the international organizations involved and their associated prime purposes.

The NASA publication, "Earth System Science, A Closer View," provides a comprehensive and concise picture of the environmental interactions which occur on time scales ranging from decades to centuries.[5] This conceptual model, shown in Figure 2, attempts to identify relationships between extrinsic variables and the predominant chemical reactions which control our environment. It also serves to portray the organized structure required for assessment of these interactions by the scientific community. The two largest rectangles represent the Physical Climate System and the Biogeochemical Cycles. Within these two broad categories are smaller rectangles representing the major subsystems. The arrows denote pathways and information flows necessary to integrate the subsystems and characterize the complete

Figure 1: International Global Research and Monitoring Organizations

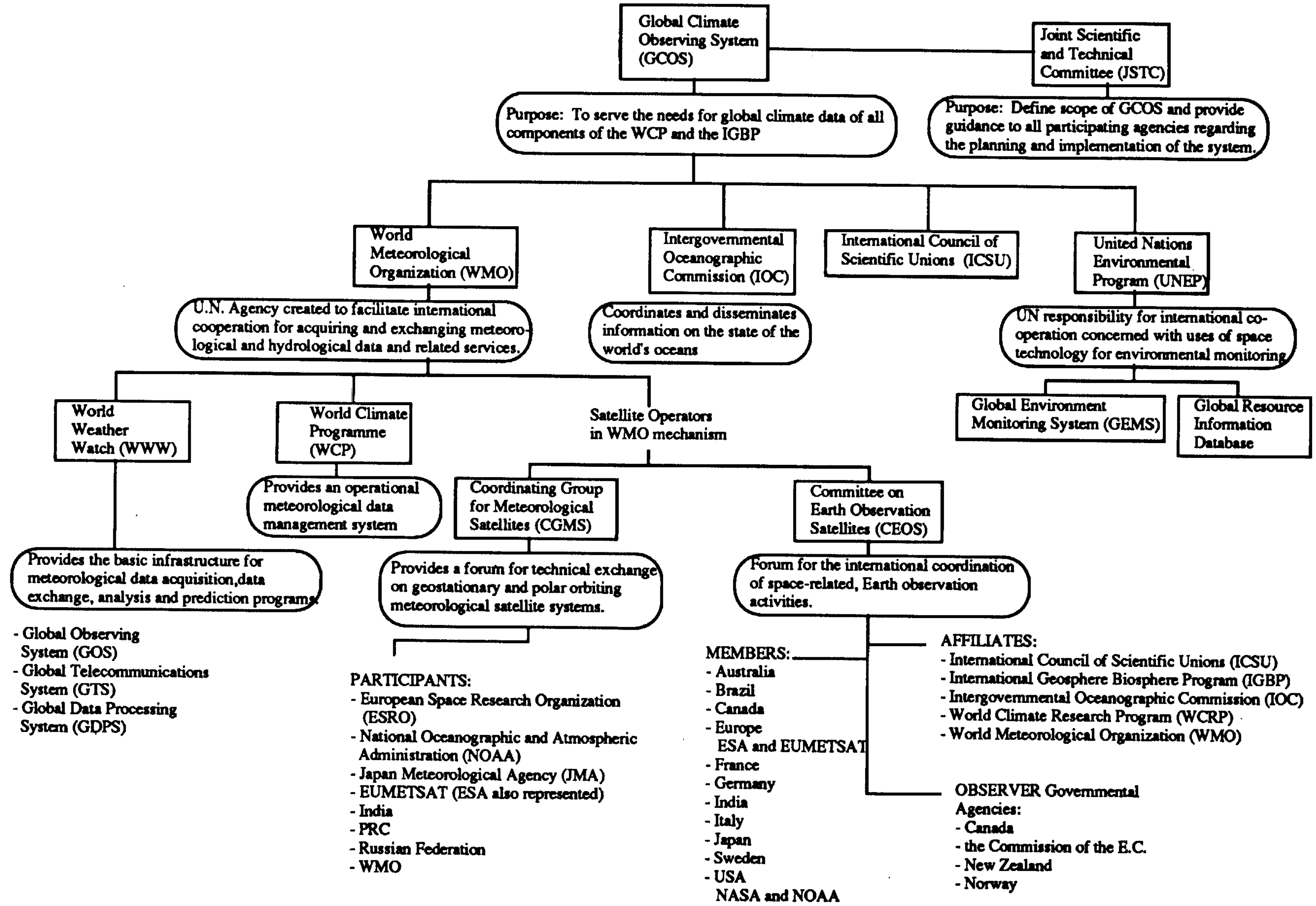
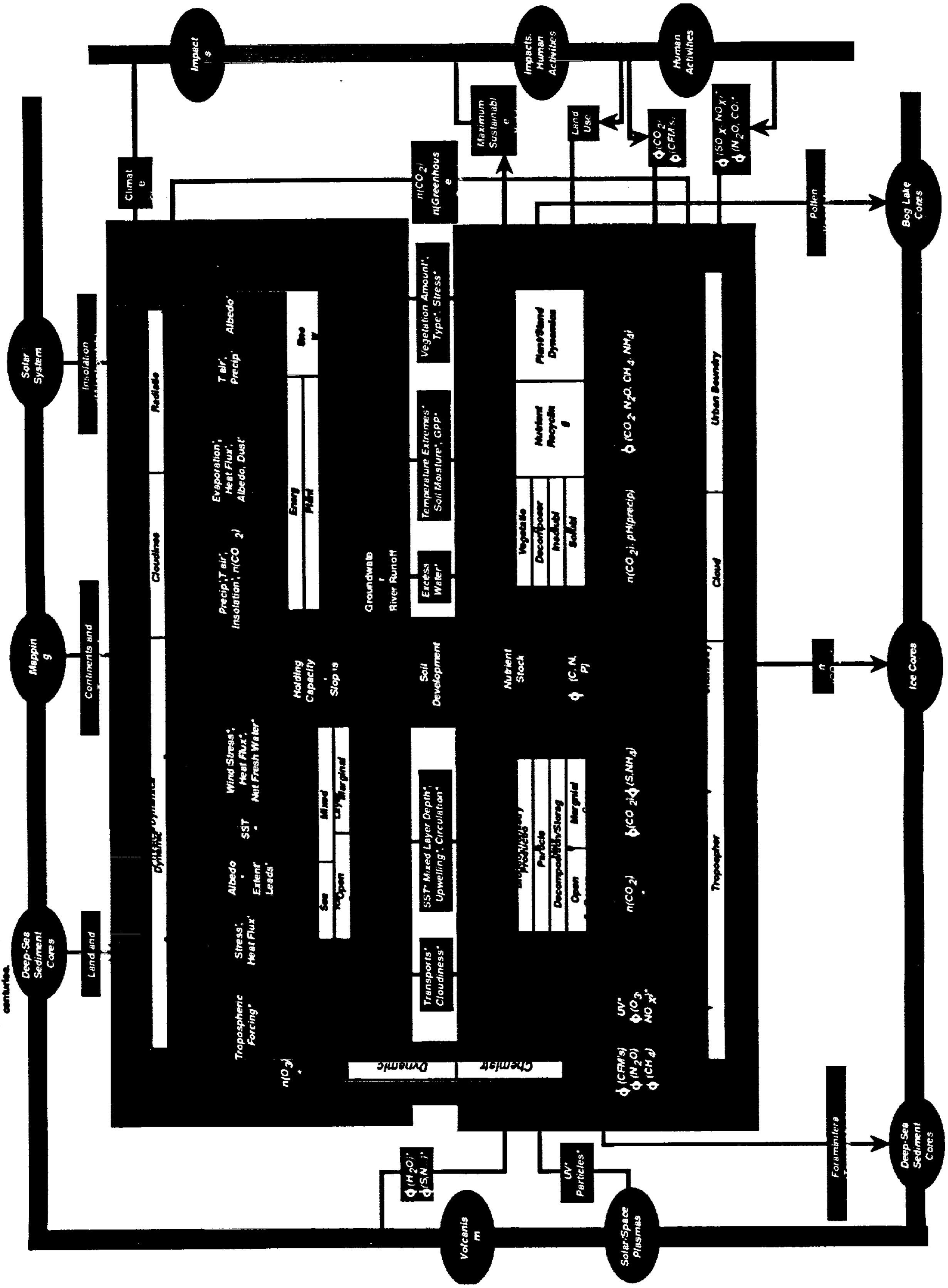


Figure 2: NASA's Conceptual Model of the Earth System on Timescales of Decades to Centuries



CONCEPTUAL MODEL of Earth system process operating on timescales of decades to centuries.

* = on timescales of hours to days ' = on timescales of months to seasons ϕ = flux n = concentration

Earth system. The ovals represent system inputs and outputs, including both naturally and anthropogenically induced sources. Each subsystem comprises a focused scientific discipline area. These scientific areas are represented by subroutines within an integrated Global Climate Change Model (GCM) to allow predictive analysis of multivariant scenarios associated with global change.

GCMs analytically model the natural and induced forces within the atmosphere, their resultant consequences and, ideally, their interactions with the Earth's land, oceans and solar boundaries.[6] These models predict probable outcomes and responses of the Earth system due to perturbations. For instance, sensitivity analysis, potential anthropogenic impacts and natural disaster scenarios may be assessed, and the resultant data evaluated for use in policy and legislative decisions.

The practice of utilizing computer models to study complex systems is widespread throughout the engineering and scientific communities. However, it is a commonly accepted fact that the performance of a model is dependent not only on the completeness, accuracy and precision of the representation and mathematically modeled interactions, but also on the data which specifies the variables. An engineering standard requires that models be verified prior to their accepted usage. Unverified model data is not typically considered acceptable information. However, if potential consequences are so dire as to preclude time for model verification and validation, the data can be treated as preliminary information, but only with the acceptance of a high level of risk.

Although they represent the best available technology, the current models inadequately account for all of the variables and interactions required to accurately predict the environment of the future.[7] This inadequacy is due to several factors: the tremendously complex nature of the Earth system, a lack of appropriate data, and the general state of the science. Furthermore, only a select few portions of the GCMs remain verified, and then only in the non-interactive portions. For example, one relevant measure of the model verification status is evident daily in the short- and long-term weather forecasts. However, the effects that weather has on the ocean currents and the Earth's overall energy and moisture balance are neither understood completely nor incorporated into the models.

Those who espouse elimination of satellite monitoring systems in favor of ground- or air-based systems do not have a clear understanding of the complexities of these issues. Some representative usages and requirements for satellite usage will serve, for the purposes of this document, to illustrate these complexities.

Chemical propulsion has had a tremendous impact in the meteorological field. The ability to launch satellites, afforded by the existence of chemical propulsion, has enabled the meteorological community to develop a global meteorological satellite network. This network, consisting of polar and geostationary orbiting satellites, complemented by a ground-based network of sensors, is operated by the WMO.[8] When combined with developments in satellite remote sensing technology, this network provides continuous, worldwide monitoring of the atmosphere. The data generated by this network is responsible for the present validation of this segment of Global Climate Models. It further enables meteorologists to identify, accurately predict and track atmospheric conditions. This ability to forecast and track weather conditions translates directly into economic savings and/or gains for many industries.

These economic gains are evident within the shipping industry. An ocean liner transporting cars from Japan to the United States, for instance, has advanced knowledge of the weather ahead on its course. If a typhoon forms in the Pacific Ocean, the company, because of satellite technology, knows the predicted course and intensity of the storm. If the ship is threatened by the storm, it can alter its planned course to avoid the weather or return to port, without jeopardizing the crew or cargo. The aviation industry has also realized significant economic benefits due to satellite technology. As in the case of the shipping industry, scheduling and routing of commercial flights are largely contingent upon the weather. Thus, human lives and millions of dollars of freight are saved from potential damage or destruction because of our ability to forecast the weather accurately.

The complexity of the Earth system processes presents perhaps the largest challenge to scientists modeling the system. Scientists are aware of some modeling unknowns, for example: How does vegetation affect the local and global climate, and vice versa? How sensitive is the climate to changes in "radiatively important trace species?" How does the ocean circulation respond to atmospheric forcing? How will changes in ocean circulation affect surface temperature distribution? How will the uptake of heat by the oceans affect the alleged global warming? How much is climate sensitivity affected by sea ice and cloud?[9] In order to answer these questions, and many others, pertinent information is necessary. For instance, accurate measurements of the absorption of long-wavelength radiation emitted from the Earth's surface by various trace gases, the distribution of water vapor in the atmosphere, associated circulation and temperatures are some variables needed to characterize the physical climate system. Further information, including sea-surface temperature and the resulting wind patterns, radiation measurements and cloudiness data all contribute to a more complete identification of the complex land-sea interaction processes. Until the gaps in existing knowledge are filled, investigators must make numerous assumptions in Global Climate Models regarding the variables' influence on the processes and their interactive roles.

The modeling unknowns can be treated in sensitivity analysis to allow resource prioritization for keying in on the critical areas, as noted above. These areas must then be assessed with proper validation techniques. This, requires the gathering of significant quantities of relevant data in order to improve our knowledge of the Earth system. The use of satellites is critical to acquiring this data. Satellites afford us the unique opportunity to monitor large areas of the earth at one time, while simultaneously collecting and transmitting the real-time data. From the vantage point of space, we can study the synoptic atmospheric dynamics. This information allows scientists to update, validate or change the fundamental assumptions made in the global climate routines. Thus, we will push the outer limits of scientific knowledge in the field of atmospheric and environmental sciences in order to gain understanding of the world on which we live.

No one single orbit can provide a complete mapping of the Earth.[10,11] Therefore, a coherent selection of satellite missions and placement, combined with polar platforms and Space Shuttle flights is necessary to achieve the defined scientific objectives via remote-sensing techniques. Current and planned space programs, particularly within NASA's Mission to Planet Earth, are designed to address some of these issues.

However, satellite data alone is not enough to ensure accurate measurement of Earth system variables. It is necessary to monitor and record environmental data in conjunction with in situ and low altitude observations in order to completely characterize a system parameter. In situ observations are useful for identifying and characterizing process variables which are more efficiently measured from space. Unfortunately, in situ measurements are often constrained by local effects. Humidity factors, precipitation, physical location (whether the sensor is near a grove of trees on next to asphalt), albedo, and so forth, all affect the in situ measurement. This site variability is difficult to account for in large scale measurement efforts extending over multiple geographical regions. Moreover, in situ observations are crucial for remote-sensing calibration and validation. Typically, sensing devices require periodic maintenance and calibration. A blend of space-based and in situ sensors ensures that sensor drift and malfunctions will be identified and corrected in a timely manner -- without resulting in excessive data loss. Low altitude data collection is also useful for characterizing complex Earth processes.[12] It provides intermediate information on the atmospheric processes, as well as performing the calibration and validation functions for space-based remote-sensors. Both in situ and low altitude observations provide discrete data points, and therefore do not furnish a concise, dynamic picture of the global climate and interactions. The use of satellites is then critical to the measurement and validation of the GCMs. Chemical propulsion is the only efficient and cost-effective mechanism we have to utilize satellites.

Satellites have a multitude of uses in commercial ventures as well. The advent of the Global Positioning System (GPS) is a good example of the commercial use of satellites, particularly in the aviation industry. The GPS uses a series of satellites to triangulate the position of an object or location, in this case, of an aircraft, equipped with an encoding receiver, and outputs the global coordinates of its position. This revolutionary aircraft tracking system eliminates the reliance on the present system of radar and tracking stations. Because of GPS, transoceanic airline flights can now follow a great circle route rather than flying within suboptimal tracking zones. It is estimated that this will save millions of dollars per year in fuel costs for transoceanic flights alone!

The total impact of the GPS will not be fully realized for many years. Its potential, however, is extraordinary. In addition to the aviation industry, the GPS has beneficial applications in diverse fields ranging from agriculture, environmental management, mining, and surveying to maritime and military operations. To operate, the GPS requires the unique perspective and range of observation that is possible only from the Earth's orbit.

In conjunction with this new technology, entire industries are being created. A similar phenomenon occurred two decades ago, during the initial development of satellite technology. The demand for commercial products such as cable television and satellite dependent cellular telephones was spawned by the availability of affordable vehicles to launch the necessary satellites. Industries which did not exist fifteen years ago now employ thousands of people and are valued in the billions of dollars. This use of satellites is achievable only through the safe, cost effective, commercial availability of chemical propulsion. Advocates who envision non-chemical, non-polluting methods for placing satellites in orbit do not have an understanding of the salient issues.

Propulsion may be thought of as the process of changing the motion of an object. Balloons, planes and rockets all serve to change the motion of their payloads, placing it either higher in (the case of balloons and planes) of outside of (in the case of rockets) the Earth's atmosphere. The atmosphere is generally broken up into four zones: the

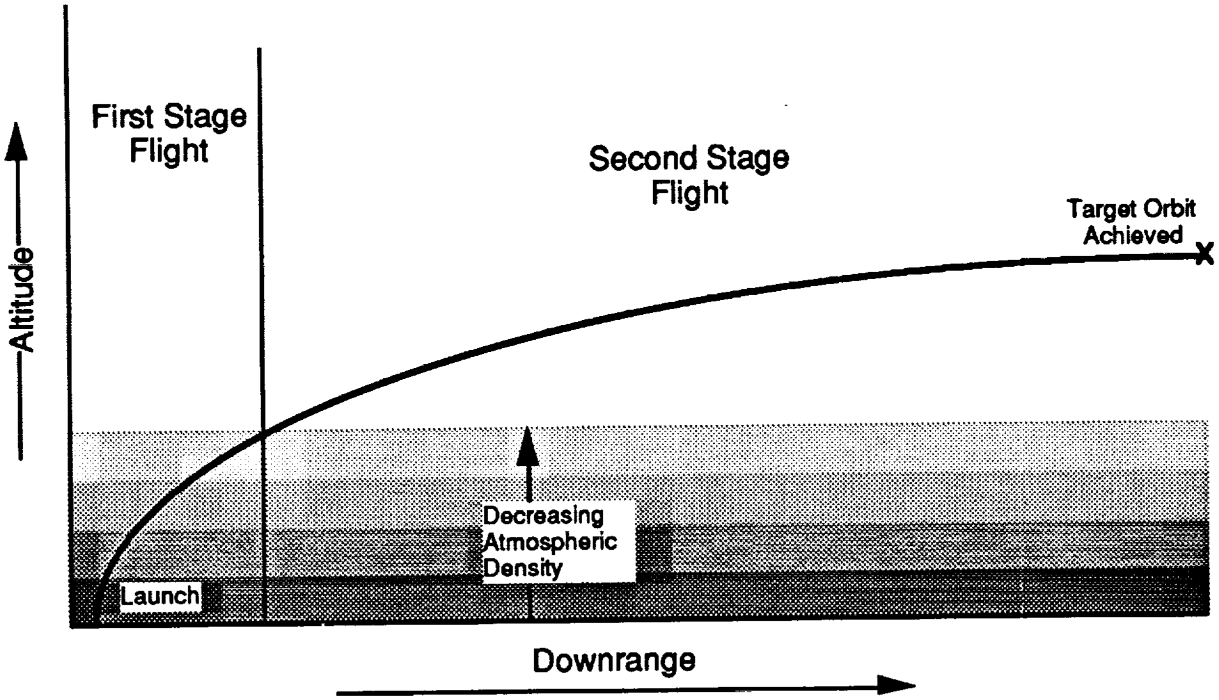
Troposphere (0 - 20 Km above sea level), the Stratosphere (20 - 50 Km above sea level), the Mesosphere (50 - 80 Km above sea level) and the Thermosphere (80 - 300 Km above sea level).[13] Only rockets can raise payloads into the thermosphere; the highest of high altitude balloons can raise payloads into the mesosphere. For the most part, jet planes are limited to the stratosphere; although, the lower levels of the mesosphere are attainable for limited systems.

The reasons that only rocket propulsion is viable for lifting payloads into the thermosphere are directly related to both the characteristics of the thermosphere and the velocities required to enter Earth orbit. The flight of a launch vehicle or space booster into orbit involves complex interactions of thrust, drag, gravity, atmosphere, winds, vehicle and payload weights, and vehicle efficiency and performance. The ascent flight profile is more analogous to a road trip by a delivery truck or the cross country flight of an airliner than the flight of a golf ball driven down a fairway or a projectile fired from a cannon. It is not only the total energy available to the vehicle in the form of propellants, but the judicious application of that energy which makes flight into orbit and deep space possible at all. Performance efficiency, or the rocket equivalent of gas mileage is called specific impulse (Isp). Specific impulse is calculated by dividing the total vehicle thrust by the total propellant flowrate.

Consider that a satellite in low earth orbit has a constant force (gravity) pulling it towards earth; the force of gravity is then balanced out by the centrifugal force of the vehicle. At the earth's surface, the required velocity to escape is 11,179 m/sec; at roughly 300 miles from the surface, the orbital velocity is approximately 7400 m/sec.[14] Today's technology precludes flight through the lower atmosphere at these velocities -- aerothermal heating alone would melt leading edges or nose cap materials. The following arguments reveal why no systems other than chemical propulsion seem feasible for placing satellites into earth orbit.

High thrust is required for a booster to rise from its launch pad, which is also when the vehicle weight is at its peak. These high thrust levels, however, are not necessary after the vehicle has passed through the dense lower atmosphere. Intermittently, thrust must be reduced during the flight, particularly during the highest aerodynamic loading, "max q," and at required points to control the acceleration loads, "g limits." A liquid engine can be throttled, and a solid motor can be designed to reduce thrust levels during portions of its burn. A typical rocket flight profile, such as the one shown in figure 3, is analogous to the operation of a truck stopped at a traffic light, then traveling up an entrance ramp onto a freeway. As the light changes to green, the driver begins to accelerate by using lower gears and pushing the accelerator to

Figure 3: A Typical Rocket Flight Profile



increase the engine output. As the truck gains speed, the need to run the engine at the high power levels diminishes, and the driver shifts into higher gears. By the time the truck reaches highway cruising speed, the engine is running at a power level which produces about 20 - 25% of its maximum horsepower.

Propulsion systems alternative to chemical propulsion have been and are being studied, but none have demonstrated the versatility that chemical propulsion exhibits. Energy can be supplied by both electromagnetic radiation and nuclear reaction. Force fields, gravitational or magnetic, have been utilized for limited types of propulsion. Nuclear energy sources inject heat to a working fluid, typically hydrogen, which then transfers kinetic energy in the form of ejecta out of a nozzle to provide propulsion. Nuclear propulsion is a special case of liquid propulsion. The high mass of the reactor and the low density of the hydrogen gas penalize its thrust capability, making it unsuitable for earth-to-orbit applications. However, nuclear propulsion provides a very high specific impulse and consistent, long duration energy source; thus it is suitable for interplanetary missions where total impulse, not thrust, is a prominent discriminator. Similarly, electric propulsion provides low thrust, long duration propulsion capability.

Electrostatic and ion propulsion do not involve the expansion of gas in a nozzle. They provide electrostatic field acceleration of ions, typically xenon, that results in vehicle thrust. Solar energy is useful in space, but also provides a low thrust, high Isp type system. The Sun is the source for a solar sail, which is external to the vehicle. These type systems are useful for attitude control, but following the rationale cited above, they are not credible for use in earth-to-orbit applications.

Earth-based accelerators, such as cannons and railguns, are also alternative sources for small payloads to reach orbital velocities. The energy, however, is applied at extremely high levels for very short intervals. The method produces severe acceleration loads, or g- forces, on the payload. Furthermore, the high initial velocities attained cause extreme aerodynamic heating and loads. Additionally, unless the payload has its own rocket motor, the variety of attainable orbits with a cannon or railgun is very restrictive. The laws of physics dictate that these orbits cannot have a perigee higher than the elevation of the launch site.

Advanced concepts, such as ion, solar, or photon propulsion exhibit the opposite problem: extremely high efficiencies, but prohibitively low thrust levels. These propulsion sources cannot produce the thrust necessary to lift off, and their physical configurations are anything but aerodynamic. There are potential applications for these systems in interplanetary flight and beyond, but they are unsuitable for the journey from a planetary surface to orbit. It is entirely possible that no scheme will ever supplant chemical propulsion in boosting a vehicle on its initial escape from the earth's surface into space.

This paper has thus far identified the necessity of chemical propulsion to satellite usage and some of the benefits we accrue through our ability to monitor global resources and patterns. The remainder identifies, in summary fashion, how the information gathered via satellite is utilized to affect national and international policies.

Undeniably, science has already forced extensive political action in response to its theories on global climate change. While NASA is not a policy setting agency, we do play a major role in the creation of legislation. NASA conducts science missions and generates much of the data necessary for inputs to Global Climate Models. It is understood within the scientific community that these rudimentary GCMs produce results which are only as accurate and complete as the information which goes into them.

The data and output from these models are utilized by policy-makers to develop and establish environmental laws and regulations. Environmental legislation is initiated in the Congress. Through its Office of Legislative Affairs, NASA will review proposed legislation, when requested, for its technical content and merit.[15,16] Again, NASA does not set environmental policy, it does, however, attempt to provide the most accurate information available to the appropriate lawmakers. It is the responsibility of the scientific community to ensure that policy-makers are aware of the fidelity of these climate models and the resulting limitations of global climate analysis and prediction. Policy-makers, in turn, must make prudent and judicious decisions based upon information available today; with the understanding that as the state of the science matures, so will our understanding of the earth's environment.

The scientific community has identified and acknowledged shortfalls in our knowledge base and in climatic model inputs. In order to remedy these shortcoming, we require large-scale and long-term monitoring of the environment. The information required is dependent upon the continued utilization of chemical propulsion to launch satellites and experiments to gather relevant data. Since models are the basis for setting environmental policies, it is both logical and imperative that we continue to support NASA's proposed course of action.

Chemical propulsion, like all environmentally conscious industries, does provide limited, controlled pollutant sources through its manufacture and usage. However, chemical propulsion is the sole source which enables mankind to launch spacecraft and monitor the Earth. The information provided by remote sensing directly affects national and international policies designed to protect the environment and enhance the overall quality of life on Earth. The resultant of chemical propulsion is the capability to reduce overall pollutant emissions to the benefit of mankind.

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